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THE LASER MEGAJOULE FACILITY: FRONT END'S CONTROL SYSTEM

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Abstract

The Laser Megajoule (LMJ) is a 176-beam laser facility, located at the CEA CESTA Laboratory near Bordeaux (France). It is designed to deliver about 1.4MJ of energy to targets, for high energy density physics experiments, including fusion experiments. Six 8-beams bundles are currently operational. The Front-End is the LMJ subsystem built to deliver the laser pulse which will be amplified into the bundles. It consists of 4 laser seeders, producing the laser pulses with the expected specificities and 88 Pre-Amplifier Modules (PAM). In this paper, we introduce the architecture of the Front-End's control system which coordinate the operations of the laser seeders and the PAMs‘s control systems. We will discuss the ability of the laser seeders and their control systems to inject the 88 PAMs almost independently. Then we will deal with the functions that enable the expected laser performances in terms of energy, spatial and temporal shapes. Finally, the technics used to validate and optimize the operation of the software involved in the Front-End's equipment performance will be detailed.

THE LASER MEGAJOULE FACILITY FRONT END'S

The Front-End's mission on the LMJ installation is to deliver a laser beam defined in terms of time shape, spatial shape and energy to the laser bundles. In this document, we will describe the functioning of the Front-End's as well as its Control Command System (CCS).

The Front-End (FE) consists of two components: the Seeders and the Pre-Amplification Modules (PAMs). The Seeder provides the laser pulses with controlled spectral and temporal characteristics to the PAMs that guarantee the spatial shape and pre-amplify the pulse before the laser bundle injection.

For the LMJ, there are four Seeders (one per Laser Hall), each Seeder delivers the laser pulses by fiber to the PAMs of their Laser Hall (Figure 1).

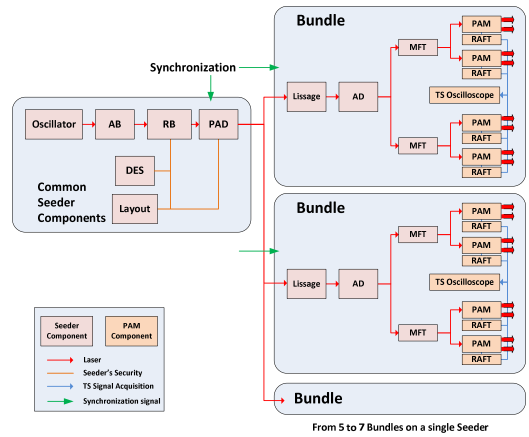

Figure 1: LMJ Front-End scheme of a Laser Hall.

THE LMJ'S SEEDER

As shown in Fig. 1, the LMJ Seeder is composed of two parts; the common part to a laser hall includes:

- The Oscillator, for the single mode 1053 nm laser pulse generation,
- The AB that performs a spectral widening to avoid Brillouin effects on the optics of the bundle,
- The RB-DES-Distri group is a functional safety device that blocks the signal if its spectral expansion is not correct,
- The PAD which Pre-amplifies and distributes the signal to the bundle bays.

Each bundle parts include:

- A smoothing module which performs a spectral widening to avoid spekel effects on the target,
- An AD module, that amplifies and distributes the signal to the MFTs,
- 1 MFT per Quadruplet (4 laser beams) that shapes the laser temporal signal. Each MFT can inject 2 PAMs.

The Seeder has an interface with the synchronization system to coordinate the operation of the LMJ's lasers.

THE LMJ'S PAM

There is one PAM for two laser beams or four per bundle. For the 22 bundles of the LMJ there are 88 PAMs.

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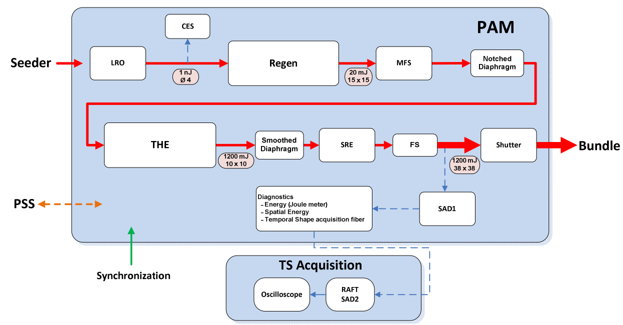

Figure 2: Schematic diagram of a PAM.

The PAM (Figure 2) is composed of the following elements:

- The *LRO* allows the two PAMs of a Quadruplet to be synchronized by increasing or decreasing an optical path at the input of the PAM,
- The *CES* verifies that the Seeder correctly injects the PAM when the system requests to work in injection mode,
- *Regen* is a regenerative cavity amplifier, the output beam is naturally a square,
- The *MFS* allows an adaptation of the spatial distribution of the energy in the beam,
- The *Notched Diaphragm* is used to define the size and edges of the beam (with a 40 order overgrowth),
- The *THE* is the high voltage flash amplifier head, it is the active element of the 4-pass amplifier,
- The *Smoothed Diaphragm* is a little larger than the Notched Diaphragm, it ensure the absence of energy around the beam,
- The *SRE* is composed of a half-wave blade and a polarizer that allows the adjustment of the energy level at the PAM's output,
- The *FS* is a Spatial Filtering, it cuts off unwanted high frequencies in the bundle,
- The *Shutter* is used to block the laser's propagation in the bundle,
- *SAD1* is a diagnostic attenuator system , the energy adaptation depends on the position of the SRE,
- The *joule meter* measures the energy at the output of the Regen cavity and at the output of the PAM,
- *SAD2* is a attenuator diagnostic system (the power adaptation, depends on the Temporal Shape,
- *RAFTs* capture a highly dynamic measurement of the temporal shape at the output of each PAM,
- The *oscilloscope* digitizes the RAFT signal for analysis and processing by the Front-End C/C System.

The PAM has a physical interface with the Personnel Security (PSS) CCS to ensure the operation of the PAM in accordance with the authorizations granted to it.

The synchronization system is used to activate the PAMs and coordinate the operation of the PAMs of the various bundles.

THE FRONT-END'S CONTROL COMMAND SYSTEM

All the Front-End's equipment (Seeders and PAMs) are controlled by a control command System. The Front-End CCS follows the nominal architecture of LMJ's Control Command (CC) System, composed of 5 layers (Figure 3). It is located only on the first 2 layers: Layer 0 (CCL0) and Layer 1 (CCL1).

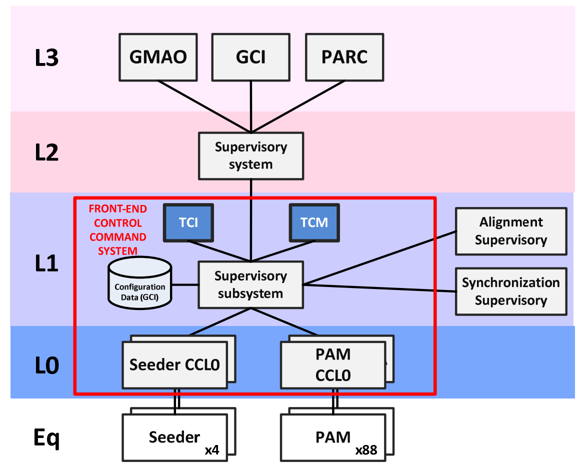

Figure 3: Architecture of FE CCS.

It is composed of:

- Two types of CCL0: Seeder's CCL0 and PAM's CCL0. Each Seeder's CCL0 supports one of the four Seeders, each PAM's CCL0 one of the 88 PAMs,
- A CCL1 that controls the different CCL0 and provides inter-CC / CCL2 control interfaces,
  Front End's dedicated software such as AMFORS, RIFT and SAFT.

FRONT-END'S CCL1

The main function of the Front-End's CCL1 is to coordinate the activities of the Seeder's and PAM's CCL0. It also provides the functions of the LMJ Front-End to the Supervisory System and to third party Supervisory Subsystems.

The "hardware" architecture of FE CCL1 is imposed by the use of the L1 Common Framework. It implements VMware virtual machines hosted within the LMJ's common control platform.

The system is composed of 6 machines:

- 1 server which hosts the databases, the log services and a local GCI necessary for the operation,
- 3 functional servers to control the resources of a laser hall; one server is available for redundancy,
- 2 operators' stations that display the operation (TCI) or maintenance (TCM) HMIs.

The FE CCL1 application uses Panorama E² using L1 Common Framework (Figure 4), it is located on both functional servers.

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The application is interfaced:

- with a local GCI and log services located on the database server, as well as the third party Supervisory Subsystems Alignment and Synchronization, using the Common Framework,
- with PAM's and Seeders CCL0, using respectively PIE-Object (External Interface Protocol) and OPC,
- with an external software named "RIFT" that allows to perform a Feedback of the Temporal Shape from the LMJ Seeder.

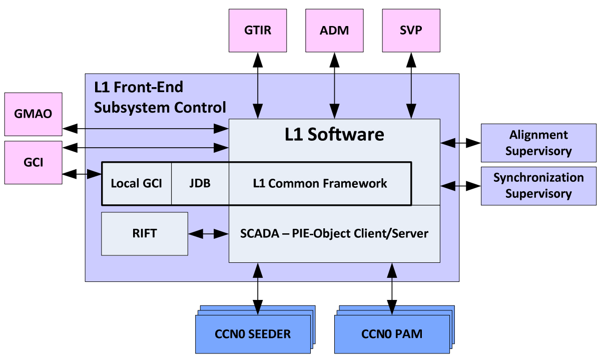

Figure 4: FE's CCL1 software architecture.

CCL1 is also in interface with the RIFT software through WCF, and shares an HDF5 exchange file (Figure 5).

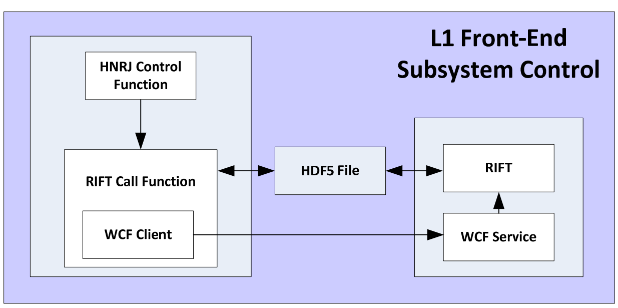

Figure 5: RIFT Interface with FE's CCL1.

FE's CCL1 includes HMIs (Figure 6) meant to control and monitor the operation of FE's equipment. They are designed to present a progressive vision of the level of detail of information: LMJ → Hall → Quadruplet → Bundle → PAM. A new design of these HMIs is to be carried out in order to synthesize several information based on the return of experience of multi-bundle operations.

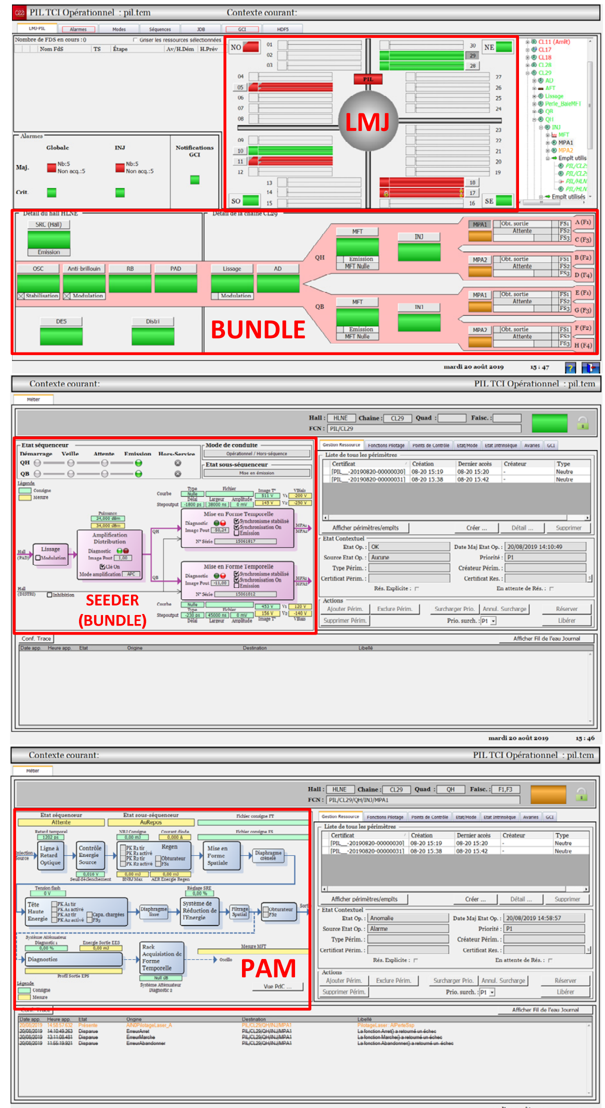

Figure 6: FE's HMI.

SEEDER'S CCL0

Each of the four Seeder's CCL0 is hosted on a Physical PC. The software is developed in C#.

The Seeder's CCL0 server is a "Service" application based on the following components:

- CCL0 Base,
- CCL0 OPC Server,
- The system configuration functions,
- The connection with the hardware drivers,
- Software traceability functions,
- Event logging functions.

This CCL0 allows to control the different equipment components of the Seeder through RS232 over TCP/IP (IOLAN Perle). Power Display Units (PDU) are also controlled by CCL0 Seeder, they allow equipment to be switched on or off (Figure 7).

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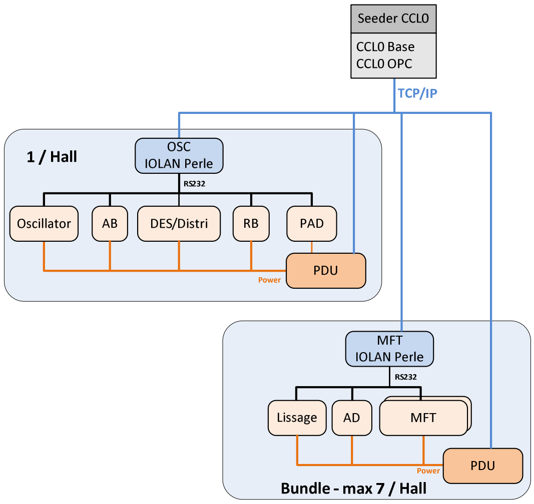

Figure 7: Seeder's control command hardware architecture.

The architecture of the Seeder's CCL0 system is represented by the following components (Figure 8):

- CCL0 Common: All components inherit from the CCL0 Common library. The CCL0 Common component makes available a library of utility functions common to the Seeder's CCL0 software.
- CCL0 Base: Base server, it is the heart of the CCL0's system; it manages the data associated with the loaded hardware configuration and serves as an interface with the hardware drivers.
- CCL0 OPC: The CCL0 OPC server acts as a gateway and interfaces with the CCL0 Base component and the OI Client / CCL1. It collects all data relating to the Seeder and its sensors, it allows an OPC client to operate and control the Seeder. The OPC Toolbox component allows to create and manage an OPC server as a.Net library. A migration to PIE-Object will be launched in the coming months.
- CCL0 Log is the software event management library.
- CCL0 Drivers is the component that exposes the definition of instruments to the CCL0 Base process.
- The HDF5.Net component is an Open Source .Net library distributed by "The HDFGroup", which allows you to create and read files in HDF5 format. This library is operated by the CCL0 Base server.
- CCL0 PDU: driver of the APC Power Display Unit.
- CCL0 IOLAN Pearl: driver of the RS232 IOLAN concentrator.
- Client OI: is an "OPC DA" type client, it operates and manages the LMJ's Seeder through the CCL0 OPC server instance.

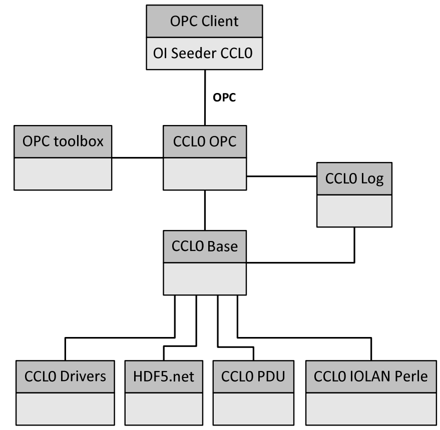

Figure 8: Software Component Architecture of Seeder's CCL0.

Each LMJ's Seeder resource (hall, bundles, Quadruplet) has a State diagram to activate its equipment as needed (Figure 9).

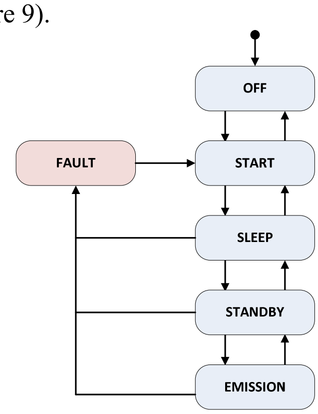

Figure 9: State diagram of an LMJ's Seeder resource.

Synchronization of Resource State

The state of the Hall resource, common to several resources, is synchronized with the bundles resources. Indeed, if a bundle needs to be in "emission" mode, the Hall part must also be in "emission" mode. Similarly, when the bundle/quadruplet resources no longer need that the Hall to be in "emission" mode, the Seeder's CCL0 automatically changes the state of this resource to "Standby". The aim here is to systematically adjust the operating state of this common resource to the needs of the bundles/Quadruplets.

PAM'S CCL0

PAM's CCL0 is integrated into the PAM's equipment. It interacts directly with PAM's modules electronic cards through FPGA or with onboard control cards.

The PAM's CCL0 interacts with various software and hardware components as follows (Figure 10):

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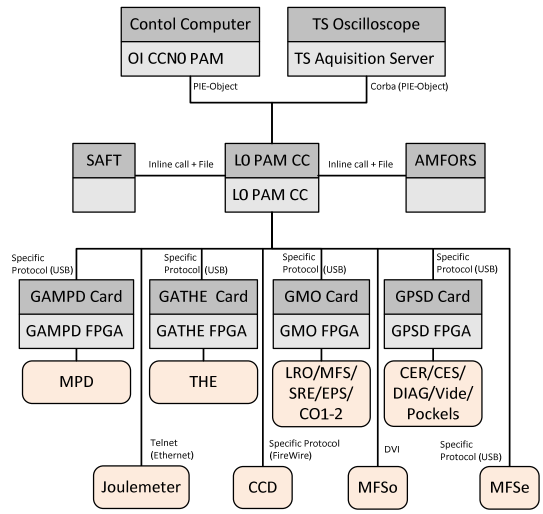

Figure 10: PAM's CCL0 Software Component Architecture.

The PAM is composed of different internal or remote electronic equipment. The main ones are:

- A computer control board: it is a motherboard based on a x86 family processor. It has different types of physical I/O interfaces that are used to control electronic equipment: USB, FireWire, Ethernet, DVI.
- Lumibird electronic equipment based on an FPGA-based architecture, it's controlled via a specific protocol through a USB interface.
- Standard electronic equipment,
- Equipment related to the active MFS:
  - a SCOR-20 camera is controlled via FireWire in order to recover the spatial shape of the beam,
  - an active matrix (DVI screen equivalent) to influence the spatial shape,
- Joule meters via Ethernet,
- The oscilloscope for acquiring the temporal shape remotely from the PAM. It's shared by the 4 PAMs of a bundle. It is currently being managed using Corba, a migration to PIE-Object is in progress.

The aim of the PAM's OI software is to control the PAM using the PIE-Object protocol. Its main functions are:

- The PAM process management ,
- The unitary management such as maintenance of PAM equipment,
- The visualization:
  - Alarms management generated by the PAM,
  - PAM's checkpoints,
- The recovery of PAM firing results.

The PAM's OI is used in the factory when qualifying PAMs before delivery to the LMJ site or as part of on-site verification.

PAM's CCL0 software is the software that provides the PAM's level 0 control interface for controlling all its equipment. The PIE-Object connector insures the interface with the FE's CCL1 and the PAM's OI. The diagram below (Figure 11) describes the different software layers used to control the PAM process equipment.

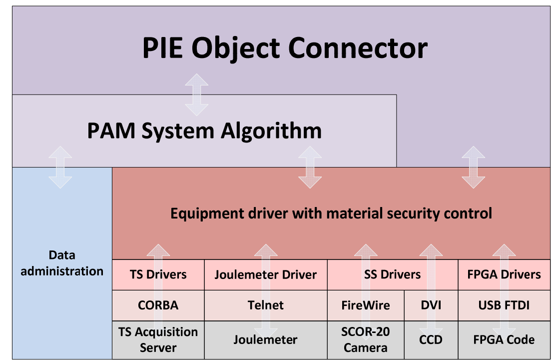

Figure 11: Decomposition of the PAM's CCL0 software layers.

The core of the PAM's CCL0 intelligence is in the system algorithms. They enable the multiple functions of the PAM to be carried out, in particular:

2 energy levels implementation:

- The Low Energy mode (150 µJ to 20 mJ) has two positions. It can either be injected by the Seeder or generate a laser pulse itself.
  - The injected mode is used for mapping LMJ KDPs.
  - The non-injected mode is used in particular for the bundle alignment. To do so, the PAM's CCL0 will seek the maximum energy by adjusting the pump current of the Regen head. The SRE will then be used to adjust PAM's output energy according to the requested set point.
- The High Energy mode (1.2 J max) is used to inject a laser pulse defined in terms of time, spatial shape and energy into the bundle. In this mode the Seeder necessarily injects the PAM. To do so, we carry out a High Energy Setup.

PAM's CCL0 has a state diagram designed to activate software and hardware components as required (Figure 12).

The PAM is manufactured and characterized at Lumibird's facilities. When it leaves the factory, it is transported in the LMJ, supplied with its own "Tracking Booklet". The FE's CC (PAM's CCL0 and CCL1) will use the content of this tracking booklet, i.e. all the settings necessary for the nominal operation of the PAM on the LMJ. This booklet will follow the PAM throughout its life cycle, allowing the configuration of the equipment to be monitored.

AMFORS

The AMFORS application, Spatial Shaping Algorithm, is written in IDL language (a migration to Python language is in progress). This software processes PAM's Spatial Shapes images in order to condition the spatial distribution of the laser beam energy. It's an IDL runtime called by the PAM's CCL0.

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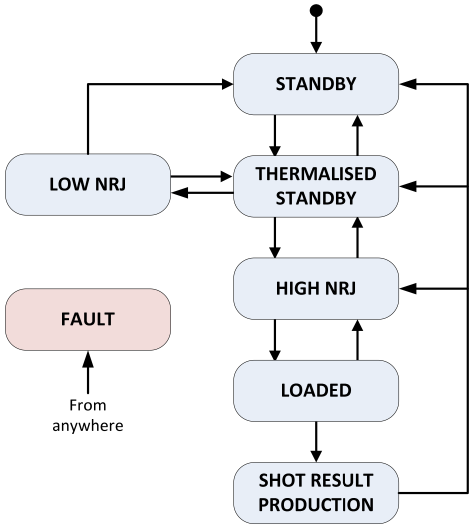

Figure 12: PAM's CCL0 state diagram.

The principle of spatial shaping is a control (or feedback) of an input control on the observation of the beam at the output, so that it corresponds to a desired shaping instruction.

The input control is applied by projecting it (using an LCD matrix) onto an optical valve, thus modifying its transmission. The observation is carried out thanks to the acquisition of PAM's camera. PAM's CCL0 sends the input data to AMFORS, which calculates the new order based on the acquisition.

RIFT

The RIFT application, Computer Time Shape Control, is written in IDL language (a migration to Python language is in progress).

The principle of temporal shaping is a control (or feedback) of an input command on the observation of the output pulse, so that it corresponds to a desired shaping requirement.

The input control is applied to the MFTs, thus modifying its transmission. The observation is carried out thanks to the acquisition of a photodiode on an oscilloscope. The CCL1, in charge of controlling the PAMs and the Seeder, transmits the input data to the RIFT, which calculates the new order for each Quadruplet based on the acquisition.

SAFT

SAFT software is integrated into the PAM module; it is used to reconstruct a high dynamic signal. It's written in IDL, the runtime is called by the PAM's CCL0.

The input signal consists of 4 successive occurrences of the same progressively amplified pulse. The amplification leads the measuring instrument to a saturation state. In order to rebuild the signal, it is therefore necessary to time shift each pulses between them according to their amplitudes. The amplification values and the delays between the successive pulses are specific to each SAFT device.

The software reconstructs the temporal shape with high dynamics. It measures the amplification factors obtained in order to verify the consistency of the results and to validate the results obtained on the reconstruction.

HIGH ENERGY SETUP

The high energy setting is a major function of the LMJ's Front-End. The FE CC System automatically adjusts the FE's equipment according to the instructions requested, namely, Temporal Shape, Space Shape and Energy. This function is divided into 6 phases; many internal laser shots are required to optimize the settings and performance. It uses the different software components presented above as well as synchronization.

- Phase 1: *Setting the Seeder*. Through the CCL0, the CCL1 activate the Seeder and programs the MFTs according to the operator's or experimenter's requirements. The injection is targeted at the Quadruplets (2 PAM) selected for the high energy setting by activating the desired MFTs. The operator can choose, if necessary, to inhibit certain PAMs.
- Phase 2: *Adjustment of the PAM's Regen head*. PAMs CCL0 algorithms will seek the maximum energy by adjusting the pump current of the Regen head.
- Phase 3: *Adjustment of the Flash voltages of the High Energy head*. PAMs CCL0 algorithm adjusts the flash voltages of the THE to obtain 1.2 J at the output of the PAM with a neutral spatial shape.
- Phase 4: *Control of the Spatial Distribution of Energy*. PAMs CCL0 adjust the MFS using feedback from AMFORS software. The software loops on this phase until the compliance rate fits with the requirement.
- Phase 5: *Control of the Temporal Shape*. In this mode, the Seeder's, PAM's CCL0 and the CCL1 are used. The adjustment of the MFT by the Seeder's CCL0 is based on feedback from RIFT. For each iteration, an acquisition of PAM's output signal is performed. In addition, the SAD2 setting is systematically adjusted by the SAFT software to obtain an optimal acquisition. The software loops on this phase until the compliance rate fits the requirement (Figure 13).
- Phase 6: Energy adjustment. At this stage, the PAM is regulated in terms of spatial and temporal shapes.
- We need to adjust the energy at PAM's output according to the desired requirement. PAM's CCL0 will do this by piloting the SRE.

At the end of the high energy setup, a file is produced and archived by the CCL1; it contains all the settings applied to the PAM's and Seeder's equipment of a Quadruplet. It will be used in the case of a "High Energy setup recall" on the same Quadruplet.

FE's operators adjust PAMs before the shooting campaigns. To do so, they perform a High Energy Setup on desired Quadruplets. When the Front-End is started for an experimental shot, the operators use the "High Energy setup recall" function. The objective is to save time and make the launch of the Front-End for shooting more reliable.

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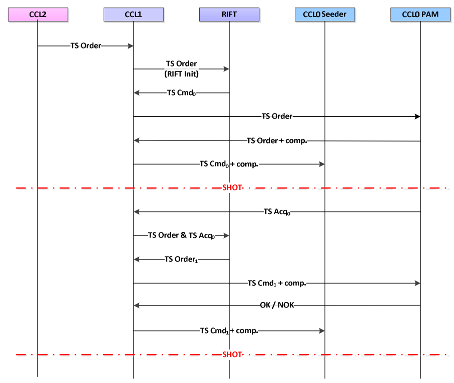

Figure 13: Flow diagram of the Temporal Shape servo control.

FE'S CC SYSTEM INTEGRATION AND VALIDATION PLATFORMS

The FE's CC evolves within a number of software platforms over its life cycle.

Outside of the LMJ:

- PFU: This is the platform for software development by the manufacturer in charge of the LMJ's CC Systems global maintenance. FE's CC system is interfaced with [CCL0+Eq] or [Eq] simulators. The equipment representativeness of the Front-End's process is not complete.
- PFI: The integration platform validates the functioning of the recently modified Front-End CC system within the rest of the LMJ's CC Systems. In this context, all process equipment is simulated.
- PAM Factory: Within this environment, PAMs are manufactured and characterized with PAMs CCL0 and their OIs. The manufacturer produces the Tracking Booklets. No validation of the FE's CC System software is possible without an impact on the PAMs production, in fact, the production schedule is dense.

On the LMJ:

- RI-PCI: This is the main platform for the operation of the Front-End on fully operational bundles with real equipment. Here, the Front-End's CC System is nominal, no software validation is allowed.
- RI-PI: This platform is used for the integration and adjustment of a new laser bundle before its commissioning. The Front-End take part of this. This platform is also not suitable for software validation because co-activity is important due to other CC integrations.

The software evolutions requested by the LMJ's operator led us to set up a new platform totally dedicated to the development of software for this CC System with real equipment (PAM and Seeder).

Indeed, the physics of a PAM or a Seeder is sometimes difficult to simulate, the development and validation of process algorithms therefore require real equipment.

The recently created RI-MCO Front-End Platform is representative of the RI-PCI Front-End CC System in terms of software and equipment. It is located on a network dedicated to the maintenance, totally separated from the LMJ's operating or integration networks.

The virtualization of machines located on the layers 1-2-3 makes the implementation of new platforms easier. Thus we were able to reproduce in addition to the Front-End CC system, as described above, its ecosystem, i. e. the Synchronization Supervisory Subsystem and the GCI. One LMJ Seeder, two PAMs and synchronization equipment are available. We can therefore validate the CCL1 and PAM's or Seeder's CCL0 software on a nominal LMJ Quadruplet.

CONCLUSION

In this paper, we have seen that the Front-End CC System is a complex subassembly with a significant impact on the laser performance of the LMJ. It was designed by pieces about 15 years ago. Different technologies are used, so updating and homogenization of technologies are necessary.

Thus, a wave of evolution of the Front-End CC System is in progress, which will be spread over several years. It will therefore improve reliability and performance of the High Energy Setup. Development paths such as Big Data or AI are being studied in order to improve the LMJ's Front-End overall performances.